

The meV mass frontier of axion physics

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(Dated: 19 August 2011)

We explore consequences of the idea that the cooling speed of white dwarfs can be interpreted in terms of axion emission. In this case the Yukawa coupling to electrons has to be $g_{ae} \sim 1 \times 10^{-13}$, corresponding to an axion mass of a few meV. Axions then provide only a small fraction of the cosmic cold dark matter, whereas core-collapse supernovae release a large fraction of their energy in the form of axions. We estimate the diffuse supernova axion background (DSAB) in the universe, consisting of 30 MeV-range axions with a radiation density comparable to the extra-galactic background light. The DSAB would be challenging to detect. However, axions with white-dwarf inspired parameters can be accessible in a next generation axion helioscope.

PACS numbers: 14.80.Va, 97.20.Rp, 97.60.Bw, 98.70.Vc

I. INTRODUCTION

The Peccei-Quinn (PQ) mechanism remains perhaps the most compelling explanation for the absence of CP-violating effects from the QCD vacuum structure [1–3]. An unavoidable consequence is the existence of the axion, the Nambu-Goldstone boson of a new $U(1)_{PQ}$ symmetry. Axions acquire a mass $m_a \sim m_\pi f_\pi / f_a$ by their mixing with neutral mesons, where $m_\pi = 135$ MeV and $f_\pi = 92$ MeV are the pion mass and decay constant, and f_a is a large energy scale related to the spontaneous breaking of $U(1)_{PQ}$. Axions generically interact with hadrons and photons. They may also interact with charged leptons, the DFSZ model [4] being a generic case. All interactions are suppressed by f_a^{-1} , so for large f_a , axions are both very light and very weakly interacting. Reactor and beam-dump experiments require $m_a \lesssim 30$ keV [3], while precision cosmology excludes the m_a range 1 eV–300 keV [5]. Sub-eV mass axions would still be copiously produced in stars. The cooling of white dwarfs (WDs), neutron stars and supernova (SN) 1987A pushes the limits to $m_a \lesssim 10$ meV [6], i.e. $f_a \gtrsim 10^9$ GeV. We here explore the impact of axions near this limit, i.e. the meV frontier of axion physics.

This range is complementary to the other extreme of the allowed axion window. During the QCD epoch of the early universe, the axion field gets coherently excited, generating a cold dark matter (CDM) fraction of $\rho_a / \rho_{CDM} \sim \Theta_i^2 (10 \mu\text{eV} / m_a)^{1.2}$ [7], where $\Theta_i = a_i / f_a$ is the initial “misalignment angle” relative to the CP-conserving value. For $\Theta_i \sim 1$, axions with $m_a \sim 10 \mu\text{eV}$ ($f_a \sim 10^{12}$ GeV) provide all of CDM and can be detected in the ADMX experiment [8]. If the reheating temperature after inflation was large enough to restore the PQ symmetry, our visible universe emerges from many domains and an average $\langle \Theta_i^2 \rangle \sim \pi^2 / 3$ has to be used. In this case, axions also emerge from the decay of topological defects and the CDM density could correspond to m_a as large as a few 100 μeV [9]. Either way, meV-mass axions provide only a subdominant CDM component.

II. COOLING OF COMPACT STARS

The most restrictive astrophysical limits on those axion models that couple to charged leptons arises from WDs. An early study used the WD cooling speed, as manifested in their luminosity function, to derive a limit on the axion-electron coupling of $g_{ae} \lesssim 4 \times 10^{-13}$ [10]. In the early 1990s it became possible to test the cooling speed of pulsating WDs, the class of ZZ Ceti stars, by their measured period decrease \dot{P}/P . In particular, the star G117-B15A was cooling too fast, an effect that could be attributed to axion losses if $g_{ae} \sim 2 \times 10^{-13}$ [11]. Over the past twenty years, observations and theory have improved and the G117-B15A cooling speed still favors a new energy-loss channel [12]. What is more, the WD luminosity function also fits better with axion cooling if $g_{ae} = 0.6\text{--}1.7 \times 10^{-13}$ [13].

While complete confidence in this intriguing interpretation is certainly premature (perhaps even in the need for a novel WD cooling itself), the required axion parameters are very specific, motivating us to explore other consequences based on the WD benchmark.

Axion cooling of SNe has been widely discussed in the context of SN 1987A [6, 14–16]. The 10 s duration of the neutrino burst supports the current picture of core collapse and cooling by quasi-thermal neutrino emission from the neutrino sphere. New particles that are more weakly interacting than neutrinos, such as the axions discussed here, can be produced in the inner SN core, leave unimpeded, and in this way drain energy more efficiently than neutrinos, which can escape only by diffusion. The SN 1987A neutrino burst duration precludes a dominant role for axions. Quantitatively, this argument depends on the model-dependent axion-nucleon couplings, the uncertain emission rate from a dense nuclear medium, and on sparse data. As we shall see, the limit does not preclude the WD interpretation, but a SN would lose a significant fraction of its energy in the form of axions.

The speed of neutron-star cooling as measured by the surface temperature of several pulsars [17] is another pos-

sible laboratory to search for axion cooling and a limit comparable to the SN 1987A bound was found [18]. However, neutron-star cooling depends even more dramatically on nuclear physics uncertainties and on the details of axion-nucleon coupling than the SN 1987A bound so that it is hard to make such arguments precise. However, if the WD interpretation applies, axion emission is another effect to be taken into account in the complicated theory of neutron-star cooling.

III. DIFFUSE SN AXION BACKGROUND

Returning to the energy loss of proto neutron stars after core collapse, axions saturating the SN 1987A limit are emitted as copiously as neutrinos. Then one not only expects a strong axion burst from each SN, but also a large cosmic diffuse background flux from all past SNe, the diffuse SN axion background (DSAB) in analogy to the diffuse SN neutrino background (DSNB) [19]. All past SNe in the universe provide a local $\bar{\nu}_e$ flux of order $10 \text{ cm}^{-2} \text{ s}^{-1}$ [19] that will become detectable in a Gd-enriched version of Super-Kamiokande [20] or a future large scintillator detector [21] with a rate of a few events per year. The estimated core-collapse rate is scaled to the amount of extra-galactic background light (EBL), representing the integrated star-formation history [22]. The intensity of the EBL is $50\text{--}100 \text{ nW m}^{-2} \text{ ster}^{-1}$, corresponding to an energy density of $13\text{--}26 \text{ meV cm}^{-3}$, i.e. about 10% of the energy density provided by the cosmic microwave background.

The present-day average core-collapse rate is $R_{cc} = 1.25 \times 10^{-4} \text{ Mpc}^{-3} \text{ yr}^{-1}$ and increases with redshift roughly proportional to 10^z until $z = 1$ and then flattens or slightly decreases [22]. Assuming that every SN releases $3 \times 10^{53} \text{ erg}$ in the form of neutrinos of all flavors and integrating over R_{cc} , properly redshifting the energy, leads to a present-day DSNB of 26 meV cm^{-3} , almost identical with the EBL. In other words, stellar populations release on average as much gravitational binding energy in the form of neutrinos as they release nuclear binding energy in the form of photons.

For meV-mass axions, therefore, the energy density of the DSAB can be comparable to the DSNB and the EBL, and indeed would be the most important axion population in the universe. The axion losses of ordinary stars would contribute a much smaller energy density, just as the neutrinos emitted by all ordinary stars contribute an energy density of only about 7% of the EBL [23, 24].

The DSAB will be calculated in analogy to the DSNB where the $\bar{\nu}_e$ spectrum as a function of present-day $\bar{\nu}_e$ energy E is given by the redshift integral

$$\frac{dN}{dE} = \int_0^\infty dz \left\{ (1+z) \varphi[E(1+z)] \right\} \left\{ R_{cc}(z) \left| \frac{dt}{dz} \right| \right\}, \quad (1)$$

where R_{cc} is the core-collapse rate. The function $\varphi(E')$ provides the number of $\bar{\nu}_e$ per rest-frame energy interval dE' released by an average SN. Notice that $N_{\text{tot}} =$

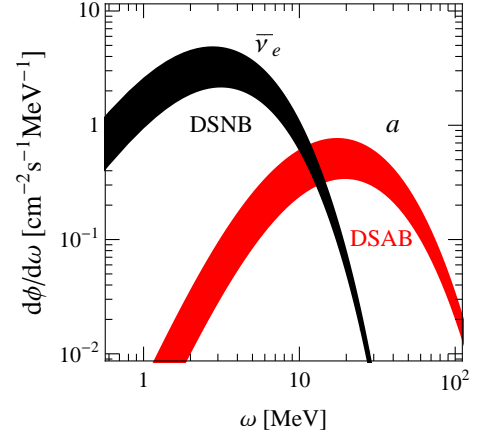


FIG. 1. Diffuse backgrounds of SN neutrinos and axions, assuming that either one carries away the full SN energy ($3 \times 10^{53} \text{ erg}$). The width of the bands reflects only the uncertainty in the core-collapse rate R_{cc} . For $\bar{\nu}_e$ a thermal spectrum with $T = 4 \text{ MeV}$ is assumed, carrying away 1/6 of the total energy, whereas for axions we use the bremsstrahlung-inspired spectrum of Eq. (8) with $T_{\text{core}} = 30 \text{ MeV}$.

$\int dE (1+z) \varphi[E(1+z)]$, the total number of neutrinos released by a SN, is invariant against redshift. Further, $|dt/dz|^{-1} = H_0(1+z)[\Omega_\Lambda + \Omega_M(1+z)^3]^{1/2}$ with cosmological parameters taken as $H_0 = 70 \text{ km s}^{-1} \text{ Mpc}^{-1}$, $\Omega_\Lambda = 0.7$, and $\Omega_M = 0.3$. Notice that $|dt/dz|$ and R_{cc} actually form one combined factor proportional to the ratio of the average luminosity per galaxy in SN neutrinos relative to stellar photons. Assuming $E_{\text{tot}} = 3 \times 10^{53} \text{ erg}$, 1/6 of this in $\bar{\nu}_e$, and $T_{\bar{\nu}_e} = 4 \text{ MeV}$ after flavor oscillations [25], we show the DSNB in Fig. 1. The width of the band reflects only the uncertainty of R_{cc} , not the uncertainty of SN neutrino emission.

IV. AXION PROPERTIES

Before estimating the DSAB we summarize the relevant phenomenological axion properties. Their mass is

$$m_a = \frac{\sqrt{z}}{1+z} \frac{m_\pi f_\pi}{f_a} = 6 \text{ meV} \frac{10^9 \text{ GeV}}{f_a}, \quad (2)$$

where $z = m_u/m_d = 0.35\text{--}0.60$ [3], but we always use the canonical value $z = 0.56$. The interaction with fermion f has the axial-vector derivative structure

$$\mathcal{L}_{af} = (C_f/2f_a) \bar{\Psi} \gamma^\mu \gamma_5 \Psi_f \partial_\mu a, \quad (3)$$

where C_f is a numerical coefficient and $g_{af} = C_f m_f / f_a$ the corresponding Yukawa coupling. For protons $C_p = [C_u - 1/(1+z)]\Delta u + [C_d - z/(1+z)]\Delta d$ and neutrons $C_n = [C_u - 1/(1+z)]\Delta d + [C_d - z/(1+z)]\Delta u$, where $\Delta u = 0.84 \pm 0.02$ and $\Delta d = -0.43 \pm 0.02$ [3]. The axion-photon interaction is

$$\mathcal{L}_{a\gamma} = -(g_{a\gamma}/4) F_{\mu\nu} \tilde{F}^{\mu\nu} a = g_{a\gamma} \mathbf{E} \cdot \mathbf{B} a \quad (4)$$

with $g_{a\gamma} = \alpha/(2\pi f_a)[E/N - 2/3(4+z)/(1+z)] \approx \alpha/(2\pi f_a)(E/N - 2)$ and E/N is the ratio of the electromagnetic and color anomalies.

We assume DFSZ axions [4] for which $E/N = 8/3$, $C_u = \frac{1}{3} \sin^2 \beta$ and $C_d = C_e = \frac{1}{3} \cos^2 \beta$. The WD value $g_{ae} = 1 \times 10^{-13}$ for the axion-electron coupling implies

$$f_a = 1.7 \cos^2 \beta 10^9 \text{ GeV}. \quad (5)$$

We choose $\cos^2 \beta = 1/2$ because much smaller values would favor SN emission over WD emission and lead to overly optimistic DSAB estimations. This choice implies $f_a = 0.85 \times 10^9 \text{ GeV}$, $m_a = 7 \text{ meV}$, $C_e = 1/6$, $C_n = 0$ and $C_p = -1/3$. Then $g_{a\gamma} = 1.0 \times 10^{-12} \text{ GeV}^{-1}$ is two orders below the CAST sensitivity [26]. The axion-nucleon couplings are $g_{an} = 0$ and $g_{ap} = 3.7 \times 10^{-10}$.

V. ESTIMATING THE DSAB

For such small couplings, axions escape freely from a SN core once produced. The dominant production process is nucleon bremsstrahlung $NN \rightarrow NN a$, but a reliable calculation has proven elusive [6]. Axions couple to the nucleon spin and are produced in spin fluctuations caused by the tensor force in NN collisions. Early calculations used nondegenerate free nucleons and a one-pion exchange (OPE) potential in Born approximation. However, if the nucleon spin-fluctuation rate Γ_σ were as large as found in these calculations, destructive interference from multiple scattering would reduce the emission rate [15]. On the other hand, based on measured NN scattering data, the spin-flip cross section was found to be much smaller than implied by the OPE approximation [16].

For a phenomenological description of the axion interaction with a nuclear medium we use the dynamical spin-density structure function $S_\sigma(\omega)$ [15, 16]. The absorption rate for axions of energy E_a is $g_{aN}^2 (\rho/8m_N^3) \omega S_\sigma(E_a)$ where ρ is the matter density. If we ignore spin correlations between different nucleons, the normalization is $\int_{-\infty}^{+\infty} S_\sigma(\omega) d\omega/(2\pi) = 1$. Emission and absorption are related by detailed balancing, implying $S_\sigma(-\omega) = S_\sigma(\omega) e^{-\omega/T}$. The spectral axion emission per unit volume is therefore

$$\frac{dQ}{dE_a} = \frac{g_{aN}^2 \rho}{16 \pi^2} \frac{E_a^4}{m_N^3} S_\sigma(-E_a). \quad (6)$$

The energy-loss rate per unit mass Q/ρ is given by $\epsilon_a = (g_{aN}^2/8\pi)(T^4/m_N^3)F$ in terms of the dimensionless integral $F = \int_0^\infty S_\sigma(-\omega)(\omega/T)^4 d\omega/2\pi$.

Low-energy bremsstrahlung is essentially a classical phenomenon. Classical spins kicked by a random force with a rate Γ_σ imply $S_\sigma = \Gamma_\sigma/(\omega^2 + \Gamma_\sigma^2/4)$ and inspire a one-parameter representation fulfilling all requirements

$$S_\sigma(\omega) = \frac{\Gamma_\sigma}{\omega^2 + \Gamma_\sigma^2/4} \frac{2}{e^{-\omega/T} + 1}. \quad (7)$$

We consider only interactions with protons (typical abundance 30% per baryon) and adopt $F = 1$ as a rough estimate so that $\epsilon_a \sim g_{ap}^2 1.6 \times 10^{37} \text{ erg g}^{-1} \text{ s}^{-1} (T/30 \text{ MeV})^4$. The SN 1987A neutrino signal duration requires $\epsilon_a \lesssim 1 \times 10^{19} \text{ erg g}^{-1} \text{ s}^{-1}$, providing $g_{ap} \lesssim 0.8 \times 10^{-9}$ [6].

Our assumptions correspond to $\Gamma_\sigma \sim 2T$. Assuming an isothermal SN core, the axion spectrum is

$$\frac{dn}{dE_a} \propto \frac{E_a^3}{E_a^2 + T^2} \frac{2}{e^{E_a/T} + 1}. \quad (8)$$

This distribution is of course not very well determined and mostly serves the purpose of illustration. With $T_{\text{core}} = 30 \text{ MeV}$ we find $\langle E_a \rangle \sim 80 \text{ MeV}$.

For our WD inspired axion parameters, a SN emits roughly 1/8 of its energy as axions. Considering all uncertainties, this fraction could be smaller or as large as 1/2, at which point it would seriously affect the SN 1987A signal. Assuming all energy is emitted in axions and with the spectral shape of Eq. (8) we find the DSAB shown in Fig. 1. The average axion energy is about 35 MeV.

VI. DETECTING THE DSAB?

Detecting this flux is extremely challenging. Axions with the parameters considered here interact much more weakly than neutrinos of comparable energy. The DSNB will be detectable in Super-Kamiokande and in next generation large-scale detectors, but the DSAB produces a much smaller signal.

One may think that conversion in large-scale astrophysical magnetic fields may provide a detectable signal. It would have to stick above the diffuse gamma-ray background in the 30 MeV region that was measured by the EGRET satellite to be $1\text{--}2 \times 10^{-6} \text{ cm}^{-2} \text{ s}^{-1} \text{ sr}^{-1} \text{ MeV}^{-1}$ [27]. Dividing the DSAB in Fig. 1 by 4π to obtain a flux per sterad, we see that the conversion probability would have to be of order 10^{-4} .

In a transverse B field and after travelling a distance L , the axion-photon oscillation probability is

$$P_{a \rightarrow \gamma} = (g_{a\gamma} B/q)^2 \sin^2(qL/2), \quad (9)$$

where $q = (m_a^2 - m_\gamma^2)/2E$. For $m_a = 7 \text{ meV}$ we can neglect the photon plasma mass in interstellar space. For $E = 30 \text{ MeV}$ the oscillation length $4\pi E/m_a^2$ is 1500 km. For these parameters, the maximum conversion rate is $P_{a \rightarrow \gamma} = 6 \times 10^{-22} (B/\text{Gauss})^2$, apparently too small for any realistic astrophysical B -field configuration. For axion-like particles (ALPs), in contrast, where m_a and $g_{a\gamma}$ are independent parameters, large conversions and astrophysical signatures are conceivable [28, 29].

The situation does not improve for $a \rightarrow \gamma$ conversions near compact objects such as pulsars or active galactic nuclei where B fields can be much larger and the photon plasma mass can be such that $q = 0$ [30]. The Hillas diagram of possible sources of high-energy cosmic rays shows that $B \times L \sim 10 \text{ G} \times \text{pc}$ can be attained.

The maximum conversion probability (taking $q \rightarrow 0$) is $(g_{a\gamma}BL/2)^2 \sim \mathcal{O}(1)$. However, the intrinsic γ -ray emission tends to be far too large to disentangle the two components, even if spectral features could help [31].

VII. NEXT GALACTIC SN

The next galactic SN will provide a high-statistics signal of 10 MeV range neutrinos [32]. What about the comparable energy release in 100 MeV range axions? The $\bar{\nu}_e p \rightarrow n e^+$ cross section is $\sigma_{\bar{\nu}_e p} \sim 9.4 \times 10^{-44} \text{ cm}^2 (E_{\bar{\nu}_e}/\text{MeV})^2$, so for detection energies of 20–30 MeV it is around 10^{-40} cm^2 . For axions, a reaction like $a + p \rightarrow N + \pi$ has a cross section on the Δ resonance ($E_a \sim 340 \text{ MeV}$) of order 100 mb $(f_\pi/f_a)^2 \sim 10^{-45} \text{ cm}^2$. Most of the axion flux is not on resonance and the rates for such reactions always seem too small for realistic detection. The largest conceivable SN signal is in a future megaton detector and if the red supergiant Betelgeuse at a distance of 200 pc collapses. This scenario provides about $3 \times 10^8 \bar{\nu}_e$ events and conceivably a few events above the tail of the neutrino spectrum that could be attributed to $ap \rightarrow N\pi$. Of course, such an scenario would require a much more careful discussion.

VIII. NEXT GENERATION AXION HELIOSCOPE

A more realistic detection possibility of WD-inspired axions is with a large helioscope beyond CAST. The conversion probability is $(g_{a\gamma}BL/2)^2 \sim 10^{-20}$ for $L = 20 \text{ m}$, $B = 10 \text{ T}$ and $g_{a\gamma} = 10^{-12} \text{ GeV}^{-1}$. The solar axion flux from processes involving electrons is $0.47 \times 10^{-6} L_\odot$ with an average energy of 2.1 keV and a flux at Earth of $2.0 \times 10^9 \text{ cm}^{-2} \text{ s}^{-1}$ [33], yielding several events per year and m^2 . The feasibility of such an instrument with an aperture up to 4 m^2 has been recently assessed [34].

One amusing application for such an instrument is to

detect axions from a possible Betelgeuse SN explosion. Assuming all SN energy is released in axions of average energy 80 MeV, Betelgeuse provides an axion fluence at Earth of $5 \times 10^{14} \text{ cm}^{-2}$. In this case one needs an aperture exceeding 20 m^2 to get a few events. Pointing the instrument at Betelgeuse in time for the explosion is possible by the early warning (\sim few days) provided by the detectable thermal neutrinos from the silicon burning phase preceding core collapse [35].

IX. CONCLUSIONS

The intriguing hint from WD cooling for the existence of DFSZ-type axions with $f_a \sim 10^9 \text{ GeV}$ and $m_a \sim 7 \text{ meV}$ implies that core-collapse SNe emit a large fraction of their energy as axions. The universe would be filled with 30 MeV-range axion radiation with a density comparable to the diffuse SN neutrino background and the extra-galactic background light. The axion population produced in the early universe would comprise only a small fraction of cold dark matter, but of course the cold dark matter in the universe may well consist of different components. Searching for a sub-dominant meV-mass axion dark matter component is a new challenge that has not yet been seriously addressed in the literature. It is intriguing that axions with such parameters are accessible in a next generation axion helioscope, a possibility that should be vigorously pursued. The interpretation of WD cooling in terms of axion emission is, of course, speculative, but it suggests a fascinating new meV-mass frontier of axion physics.

ACKNOWLEDGMENTS

G.R. and J.R. acknowledge partial support by the Deutsche Forschungsgemeinschaft, Grants No. TR 27 and EXC 153 (Germany), N.V.M. by MECESUP Project PUC0609 (Chile).

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